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The Effect of Suture Locking on the Biomechanical Performance of a Multistrand Flexor Tendon Repair

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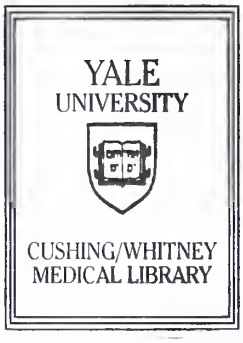
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A Thesis Submitted to the
Yale University School of Medicine
in Partial Fulfillment of the Requirements for the
Degree of Doctor of Medicine

By
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THE EFFECT OF SUTURE LOCKING ON THE BIOMECHANICAL PERFORMANCE OF A MULTISTRAND FLEXOR TENDON REPAIR

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Although early active motion protocols following zone II flexor tendon repairs have improved patient outcomes, they demand repairs with high tensile strength and resistance to gap formation. Locking loops, although demonstrated to increase the strength of two strand repairs (1) may adversely affect the performance of multistrand repairs by causing uneven distribution of tension between strands. A new *in situ* dynamic testing apparatus was developed to determine whether the nonlocked Cruciate repair (2) would demonstrate improved biomechanical performance in comparison to a Cruciate repair with locking loops. Twenty flexor digitorum profundus tendons from fresh frozen cadaver hands were lacerated transversely and repaired *in situ* in zone II using either a nonlocked Cruciate or locked Cruciate repair. Ultimate tensile strength, resistance to gap formation and work of flexion were measured simultaneously on a tensile testing apparatus. The Student′ s two-tailed t-test was used for statistical analysis. No statistically significant differences were found between the locked Cruciate and nonlocked Cruciate with respect to ultimate tensile strength ($p < 0.05$). With the numbers of fingers tested, no significant differences in work of flexion and resistance to two mm, three mm and four mm gap formation were detected ($p < 0.05$). Our findings suggest that locking of multistrand repairs poses no biomechanical advantage, and may in fact have deleterious effects by facilitating load maldistribution among the suture strands. Nonlocked repairs allow suture gliding so that the tensile load across the repair site is distributed evenly among the longitudinal strands. Although locked and nonlocked tendon repairs are biomechanically comparable, nonlocked repairs have several clinical

advantages. Nonlocked repairs are technically easier to perform and pre-tension than locked repairs.(2) Locked repairs leave more suture material exposed to the flexor tendon sheath and require more operative manipulation of the tendon, so the risk of postoperative adhesions is increased. (3,4,5)

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Table of Contents:

Title 1

Abstract 2-3

Acknowledgements 4

Introduction 6-7

Statement of Purpose and Hypothesis 8

Methods

Specimen Preparation and Pre-Repair Biomechanical Testing . 9

Gap Monitoring 9

Surgical Technique 10

Post-Repair Biomechanical Testing 10-11

Results 12

Table 1. 12

Discussion 13-14

Figure 1. 15

Figure 2. 16

References 17-19

Introduction:

Although early active motion protocols have improved the outcomes of zone II flexor tendon repairs (6-11), they have also increased the risk of repair rupture and gap formation during rehabilitation. These post-operative protocols demand that repairs have high tensile strength and resistance to gap formation in order to tolerate the increased forces generated by active motion. Efforts to develop stronger repairs have resulted in innovations in suture materials (12-14), core suturing techniques (9, 15-17), and peripheral cirumferential suturing techniques.(18,19) There is unequivocal evidence that increasing the number of strands crossing the repair site correlates directly with the repair's ultimate tensile strength and resistance to gap formation, and several multistrand repairs have been proposed.(12, 16, 17,20-22)

One of the drawbacks of multistranded and augmented flexor tendon repairs has been a demonstrated increase in work of flexion.(23) Recent attention has been focused on altering the design of repairs to yield improved tensile strength without increasing the bulk and difficulty of the repair. One such method is to incorporate locked loops in the tendon repair, in an effort to obtain better grasp on the tendon fibers and prevent suture pull-out. Pennington was the first to describe the "locking loop" by highlighting the importance of orientation of the transverse and longitudinal intratendinous components of the suture. When tension is applied to a repair in which the transverse component passes superficial to the longitudinal component, a loop of suture locks around a small bundle of tendon fibers.(24)

The effect of locking loops on the biomechanical properties of multi-strand repairs and the mechanism of action of the locked loops remains controversial. Some authors believe that a repair' s ability to convert the longitudinal tension into a transverse

compressive force on the tendon fibers contributes directly to its ultimate tensile strength. (1, 13, 17) Other investigators believe that locking loops do not contribute to the ultimate tensile strength of repairs and may even lead to gap formation at low or moderate loads.(3, 22, 25)

Statement of Purpose and Hypothesis:

McLarney et al. introduced the Cruciate repair and demonstrated its ability to tolerate linear loads in a cadaveric model that were well above the projected forces of active motion protocols. (2) The current study measured the effects of locking loops on ultimate tensile strength, resistance to gap formation and work of flexion of the Cruciate repair. We hypothesized that the nonlocked Cruciate, which allows gliding of the suture to equilibrate the tensile load between the four longitudinal stands, would show higher ultimate tensile strength and increased resistance to gap formation when compared with the locked Cruciate repair.

Methods:

Specimen Preparation and Pre-Repair Biomechanical Testing

Twenty index, long and ring fingers were disarticulated at the metacarpal-carpal joint of seven fresh frozen cadaver hands. A midlateral incision was made in each digit over zone II of the flexor tendon sheath. A window was created in the flexor tendon sheath to expose the region between the A2 and A4 pulleys. The skin was closed with simple sutures. The digit was secured to an *in situ* tensile testing apparatus via two 7/64 inch threaded Steinmann pins, which were drilled into the metacarpal. The flexor digitorum profundus tendon being tested was attached to a load cell. The flexor forces were antagonized by the extensor comminus tendon, which was attached to a 200 g mass to insure complete interphalangeal joint extension. The metacarpophalangeal (MP) joint was maintained at 10 degrees flexion to mimic the effect of the lumbricals under physiological conditions.(26) The FDP tendon was preloaded to a tension of two newtons and the platform was translated twenty mm at a constant rate of forty mm/min. Force data from the load cell and excursion data from an attached linear variable displacement transducer (LVDT) were simultaneously recorded by a computer. (Figure 1.) A force-excursion curve was generated for each tendon tested, and the area under the curve was calculated as the baseline value for work of flexion.

Gap monitoring

After completion of the baseline run, the finger was kept mounted in the testing apparatus for preparation of the fluoroscopic analysis. Two simple knots were made in a 4-0 monofilament steel suture (Ethicon, Somerville, NJ) approximately 1 cm apart. The previous incision was opened and the suture placed longitudinally within the tendon in

the A2-A4 repair window, to allow for continuous fluoroscopic monitoring of tendon excursion. The skin was sutured closed and a second force-excursion curve was generated to control for the effect of the intratendinous markers on work of flexion. The digit was then removed from the testing apparatus and the FDP tendon and intratendinous metallic marker were transversely lacerated in zone II so that one metal knot was on each side of the laceration.

Surgical Technique

All repairs were performed under 2.5 X loupe magnification by the same surgeon. Core sutures were performed with 4-0 braided polyester suture (Ethibond, *Excel*, Ethicon, Somerville, NJ), and a peripheral, circumferential locking sutures was performed using a 6-0 monofilament nylon suture (Ethilon, Ethicon, Somerville, NJ). Ten tendons were repaired using the nonlocked Cruciate technique as described by McLarney et al. The ten locked Cruciate repairs were configured similarly but were locked at the surface of the tendon with Savage-type grasps at the four corners.(17) (Figure 2.)

Post-Repair Biomechanical Testing

During load to failure testing, gap formation at two mm, three mm and four mm was monitored via a mini-fluoroscopy unit (XiTec, Windsor, CT) using an image capture program and frame grabber (Data Translation Inc., Marlborough, MA). One hundred twenty fluoroscopic images per minute of the tendon and intratendinous markers were recorded to the attached PC. Time was used to synchronize the images with the force and excursion data. A reference scale mounted coplanar to the intratendinous markers was used to calibrate the gap measurements represented by the increasing distance between the markers. Ultimate tensile strength was the maximum force recorded by the load cell.

The increase in work of flexion was calculated by normalizing the change in work of flexion after the repair to the baseline work of flexion. Statistical analysis was performed using the Student's two-tailed t-test and significance determined at $p < 0.05$.

N.B. All flexor tendon repairs and drilling of Steinmann pins into metacarpals was done by Dr. Kimberly Barrie. All biomechanical testing, data collection and statistical analysis was done by Dinakar Shenbagamurthi.

Results:

There was no statistically significant difference in mean ultimate tensile strength between the locked Cruciate (79 ± 9 N) and the nonlocked Cruciate (70 ± 7 N). ($p < 0.05$, power = 0.7). With the numbers of repairs tested, there were no significant differences between the locked and nonlocked repair techniques in ability to resist gap formation (Table 1). The nonlocked repair tolerated slightly higher two mm gap loads than the locked repair, but the trend was reversed for three and four mm gaps. At each gap measurement, however, there was a consistent trend showing a higher load tolerated for the nonlocked repairs when expressed as a percentage of ultimate tensile strength. The mean ± SD increase in post-repair work of flexion of the locked Cruciate (29 ± 20 %) was higher than that of the nonlocked Cruciate (25 ± 20 %), but again the results were not statistically significant with the numbers of repairs tested.

Table 1. Gap Formation of the Nonlocked Cruciate and Locked Cruciate.

	Nonlocked Cruciate (mean ± SD)		Locked Cruciate (mean ± SD)		
	Newtons	% of UTS	Newtons	% of UTS	p value
Load at 2 mm Gap	37 ± 18	52 ± 22	35 ± 17	44 ± 19	NS
Load at 3 mm Gap	49 ± 15	70 ± 17	52 ± 14	65 ± 15	NS
Load at 4 mm Gap	57 ± 12	81 ± 12	61 ± 14	77 ± 13	NS

With the numbers of specimens tested, no statistically significant differences in gap formation were found using the Student's two-tailed t-test. The nonlocked cruciate tolerated a consistently higher load, measured as a percentage of ultimate tensile strength, than did the locked cruciate.

Discussion:

We introduced a dynamic *in situ* method to simultaneously monitor load, gap formation, and work of flexion of zone II flexor tendon repairs. In this study, locked and nonlocked four-strand flexor tendon repairs were demonstrated to be similar with respect to ultimate tensile strength, work of flexion and resistance to two mm, three mm and four mm gap formation. A consistent trend showed that the nonlocked design tolerated a higher percentage of its ultimate strength before gapping at each gap level than the locked design. (Table 1) This finding may be attributable to the ability of a nonlocked repair to allow suture gliding so that the tensile load across the repair site is distributed evenly among the four longitudinal strands.

The problem of load maldistribution was documented by Mashadi and Amis who studied the failure mechanism of locking loops in human cadaver tendons and found that locking loops failed sequentially rather than through load sharing.(3) They noted that with sequential loading, increasing the number of locking loops did not improve the ultimate tensile strength. They also found that increasing the number of locking loops actually resulted in greater gap formation because under high tensile load the locking loops collapsed liberating more suture material from the tendon end. The finding of Mashadi and Amis that locking loops do not improve ultimate tensile strength was confirmed by Bhatia *et al.*(27) who studied locking loops in a Kessler configuration by load-to-failure and cyclic testing and by Wagner *et al.*(22) who performed an *in vivo* canine study. Strickland also noted that locking loops may collapse and lead to gap formation at moderate loads.(25)

Our findings are in contrast to those of Hotokezaka and Manske, who studied pullout strengths of locking and grasping two-strand suture configurations in human

cadaver tendons.(1) They found that incorporating one locking configuration per strand maximized the pullout strength of two strands of suture from a tendon end. Use of such a two-strand model would be expected to minimize the effect of load maldistribution and pre-tensioning difficulty that is inherent to a locked multistrand suture configuration, and may explain the discrepancy between this and previous reports. In addition, an *in situ* dynamic model is likely a more physiologically accurate and rigorous test of the biomechanical performance and gap potential of a tendon repair than a linear pullout model.

Nonlocked tendon repairs have several advantages over locked repairs in broad clinical use. Nonlocked repairs are easier to pre-tension during placement than locked repairs, and require considerably less time and operative handling of the tendon.(2) While Savage acknowledged that tying all the knots of various simple suture loops with the same tension is impossible, he failed to acknowledge that assuring equal tension in the multiple strands of locking repairs is also nearly impossible.(17) Increased operative manipulation of the tendon during tendon repair increases the potential for adhesion formation during the postoperative period.(3, 4) Locked repairs also leave more suture material exposed to the flexor tendon sheath, further increasing the risk of postoperative adhesions.(5)

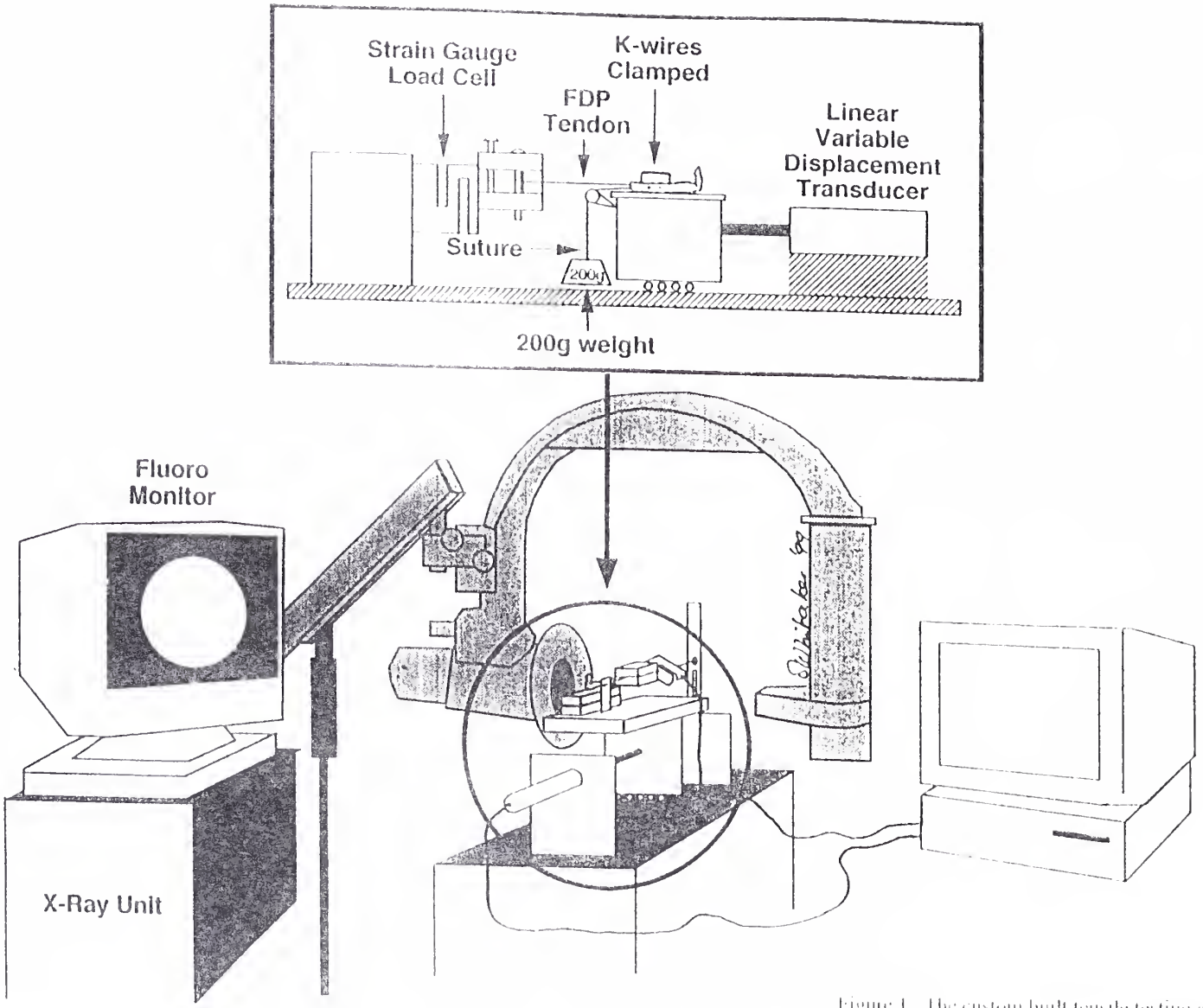
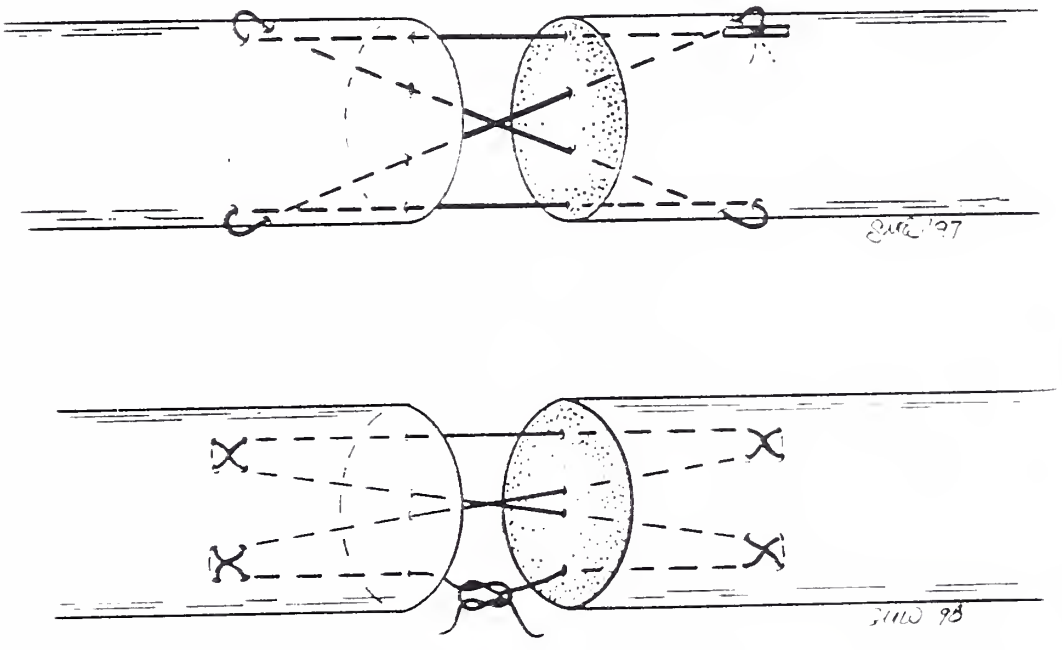


Figure 1. The custom built tensile testing apparatus

Figure 2. The two suture techniques tested included the (top) nonlocked Cruciate, and the (bottom) locked Cruciate.



References

1. Hotokezaka, S. and Manske, P.R. Differences between locking loops and grasping loops: effects on a 2-strand core suture. *J. Hand Surg. [Am].* 22A: 995-1003, 1997.

2. McLarney, E.; Hoffman, H.; and Wolfe, S.W. A biomechanical analysis of the Cruciate four strand flexor tendon repair. *J. Hand Surg. [Am].* 24A: 295-301, 1999.

3. Mashadi, Z.B. and Amis, A.A. The effect of locking loops on the strength of tendon repair. *J. Hand Surg. [Br].* 16B: 35-39, 1991.

4. Potenza, A.D. Critical evaluation of flexor-tendon healing and adhesion formation within artificial digital sheaths: An experimental study. *J. Bone Joint Surg. Am.* 45A: 1217-1233, 1963.

5. Verdan, C. : Reparative surgery of flexor tendons in the digits. In Tendon surgery of the hand, pp. 57-66. New York, Churchill Livingston, 1979.

6. Becker, H.; Orak, F.; and Duponselle, E. Early active motion following a beveled technique of flexor tendon repair: Report of fifty cases. *J. Hand Surg. [Am].* 4: 454-460, 1979.

7. Brunelli, G.; Visagio, A.; and Brunelli, F. Slip-knot flexor tendon suture in zone II allowing immediate mobilization. *Hand,* 15: 352-358, 1983.

8. Cullen, K.W.; Tolhurst, P.; Lang, D.; and Page, R.E. Flexor tendon repair in zone 2 followed by controlled active mobilization. *J. Hand Surg. [Br].* 14B: 392-395, 1989.

9. Lee, H. Double loop locking suture: a technique of tendon repair for early active mobilization. Part II: Clinical experience. *J. Hand Surg. [Am].* 15: 953-958, 1990.

10. Messina, A. The double armed suture: tendon repair with immediate mobilization of the fingers. *J. Hand Surg. [Am].* 17: 137-142, 1992.

11. Small, J.O.; Brennen, M.D.; and Colville, J. Early active mobilisation following flexor tendon repair in Zone 2. *J. Hand Surg. [Br].* 14B: 383-391, 1989.

12. Trail, I.A.; Powell, E.S.; and Noble, J. An evaluation of suture materials used in tendon surgery. *J. Hand Surg. [Br].* 14B: 422-427, 1989.

13. Urbaniak, J. R.; Cahill, C. J.; And Mortenson, R. A. Tendon suture methods: Analysis of tensile strength. In AAOS symposium on Tendon Surgery in the Hand, pp. 70-80. St. Louis, CV Mosby, 1975.

14. Wade, P.J.F.; Muir, I.F.K.; and Hutcheon, L.L. Primary flexor tendon repair: the mechanical limitations of the modified Kessler technique. *J. Hand Surg. [Br].* 11B: 71-76, 1986.

15. Kim, S.K. Further evolution of the grasping technique for tendon repair. *Ann. Plast. Surg.* 7: 113-119, 1981.

16. Robertson, G.A. and al-Qattan, M.M. A biomechanical analysis of a new interlock suture technique for flexor tendon repair. *J. Hand Surg. [Br].* 17: 92-93, 1992.

17. Savage, R. In vitro studies of a new method of flexor tendon repair. *J. Hand Surg. [Am].* 10B: 135-141, 1985.

18. Ion, L.E.; Sykes, P.J.; Cassell, O.C.S.; O'Doherty, D.M.; and Roberts, A.M. Comparative biomechanical analysis of a new circumferential flexor tendon repair and a modified Kessler repair. *Br. J. Plast. Surg.* 50: 236-241, 1997.

19. Lin, G.T.; An, K.N.; Amadio, P.C.; and Cooney, W.P., 3d: Biomechanical studies

of running suture for flexor tendon repair in dogs. *J. Hand Surg. [Am].* 13A: 553-558, 1988.

20. Boulas, H.J. and Strickland, J.W. Strength and functional recovery following repair of flexor digitorum superficialis in zone 2. *J. Hand Surg. [Br].* 18: 22-25, 1993.

21. Silfverskiold, K.L. and Andersson, C.H. Two new methods of tendon repair: an in vitro evaluation of tensile strength and gap formation. *J. Hand Surg. [Am].* 18: 58-65, 1993.

22. Wagner, W.F., Jr.; Carroll, C., 4th; Strickland, J.W.; Heck, D.A.; and Toombs, J.P. A biomechanical comparison of techniques of flexor tendon repair. *J. Hand Surg. [Am].* 19: 979-983, 1994.

23. Aoki, M.; Manske, P.R.; Pruitt, D.L.; Kubota, H.; and Larson, B.J. Work of flexion after flexor tendon repair according to the placement of sutures. *Clin. Orthop.* 205-210, 1995.

24. Pennington, D.G. The locking loop tendon suture. *Plast. Reconstr. Surg.* 63: 648-652, 1979.

25. Strickland, J.W. Flexor tendon injuries: I. Foundations of treatment. *J. Am. Acad. Orthop. Surg.* 3: 44-54, 1995.

26. Greenwald, D.; Shumway, S.; Allen, C.; and Mass, D. Mechanical analysis of human hand function: a dynamic model. *J. Hand Surg. [Am].* 19A: 626-635, 1994.

27. Bhatia, D.; Tanner, K.E.; Bonfield, W.; and Citron, N.D. Factors affecting the strength of flexor tendon repair. *J. Hand Surg. [Br].* 17: 550-552, 1992.

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